PL-TN--93-1022

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93-1022

# A PHOTOREFRACTIVE RING RESONATOR OPTICAL ASSOCIATIVE MEMORY

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October 1995

Final Report



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This final report was prepared by the Phillips Laboratory, Kirtland Air Force Base, New Mexico, under Job Order ILIR9005. The Phillips Laboratory Project Officer-in-Charge was Dr. Mark Kramer (LIAE)

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# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | October 1995 | Final Jan 90-Dec 90 |

**4. TITLE AND SUBTITLE**

A PHOTOREFRACTIVE RING RESONATOR OPTICAL ASSOCIATIVE MEMORY

**5. FUNDING NUMBERS**

PE: 61101F
PR: ILIR
TA: 90
WU: 05

**6. AUTHOR(S)**

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Mark A. Kramer, Ph.D.

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Phillips Laboratory
3550 Aberdeen Ave
Kirtland AFB, NM 87117-5776

**8. PERFORMING ORGANIZATION REPORT NUMBER**

PL-TN-93-1022

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**

Approved for public release; distribution is unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

Optical associative memories (OAM's) can recall stored images from partial or noise-degraded input images. One proposed way to implement an OAM is to store the desired images as holograms in a ring resonator geometry. If certain conditions are met, these images can be retrieved from partial or noisy inputs. The seperate components of this scheme were investigated in several small experiments. Limitations and drawbacks of the ring resonator approach were discovered, and the desired associative memory system performance was not acheived.

**14. SUBJECT TERMS**

Photorefractive, Associative Memory

**15. NUMBER OF PAGES**

14

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | SAR |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

## 1.0 INTRODUCTION

Associative memories are memories in which the stored information is addressed by its content rather than its location, as in conventional computer implementations. In an autoassociative memory, the input information recalls the stored version of itself. For example, an image of the letter "A" could recall a stored letter "A." The usefulness of this device is that the input "A" image does not have to be perfect to retrieve the ideal stored "A." As long as the input is "similar enough" to the stored image, it will be recognized, and in fact classified, as an "A." A certain amount of noise/or obscuration can be present and the system can still interpret the input as the correct image. Thus, the major application of these fault-tolerant associative memories is to perform automatic image classification.

It is very desirable to implement associative memories and other image processing devices in optics rather than electronics, since the potential processing speed is much greater with optics. Also complex software and electronic hardware must be used to perform functions which are implemented straightforwardly in the optical domain, as in the well-known example of the two-dimensional Fourier transform.

There are many approaches to implementing associative memories and image classifiers in optics. One important distinction is between linear and nonlinear methods. Nonlinearity in the system allows more sophisticated decision-making to occur. For example, nonlinearity in an optical associative memory (OAM) allows the system to output the single stored image that the input is most similar to. A linear system would respond with a superposition of the similarities between the input image and each of the stored images. These separate correlations would then have to thresholded (a nonlinear process) in order to classify the input. Even within the class of nonlinear OAM's, there are many types of implementations. A recent review paper (ref.1) lists seven different approaches which all use holography.

One of these approaches involves the use of a ring resonator in which gain is supplied via two-beam coupling in a photorefractive material (ref.2). Images are stored in a hologram which serves as one mirror of the resonator. The image wavefronts become the "modes" of the resonator. Then, when the light is injected into the resonator, in the form of a partial or corrupted version of one of the stored images, it will excite each "mode," or stored image, to the degree that it is similar to it. However, competition for gain in the photorefractive material will cause one mode, the most similar one, to achieve gain at the expense of the less similar modes. This effect is amplified by the resonators feedback, and eventually the resonator should arrive at a steady-state output consisting of only the most similar stored image. This is a simple description of the desired performance of such a device. The underlying interactions in a photorefractive material in a resonator are very complex.

## 2.0 PHOTOREFRACTIVE RING RESONATOR

### 2.1 Two beam coupling in barium titanate

For the proposed system to perform as an associative memory, it is necessary to have sustained oscillation in the ring resonator. The gain in the resonator is to be provided by two-beam coupling in barium titanate. This gain must be sufficient to overcome the losses due to the mirrors and the beamsplitters in the resonator, as well as the limited diffraction efficiency of the hologram containing the stored images.

A simple optical setup was used to investigate the net gain that could be achieved with barium titanate. (See fig. 1) Several models of helium-neon lasers were used, and three different barium titanate specimens were investigated. A Uniphase model 1105P laser was chosen as having the most stable output power. The path lengths of the two beams were equalized to within 5 mm by careful measurement to assure maximum coherence between the beams. (The HeNe laser was assumed to be running in several longitudinal modes.) The laser light was horizontally polarized by at least a ratio of 100:1. The crossing angle of 2R = 40 degrees was chosen as being close to the optimum angle for two-beam coupling gain (ref.3). The power in each beam was measured 1) without the crystal in the setup, 2) with each beam going through the crystal separately, and 3) after the two beams had interacted in the crystal for approximately one minute. Typical results are summarized in Table 1 for the case of equal intensity beams and the case where one beam is 10 times more intense. Note the large insertion loss of the crystal. The average transmission of the four beams measured in Table 1 is only 66%. In the equal intensity case, the resulting net gain is very small (5%), while in the other case it was 270%. In all cases, the observed two-beam coupling intensities fluctuated greatly, varying between values shown on lines 2 and 3 of Table 1. Although these results were not encouraging, they indicated that a ring resonator might be sustainable, if the losses did not exceed 60% per round trip.

### 2.2 Ring resonator without holographic element

A ring resonator formed by four aluminum mirrors was set up as shown in Fig. 2. The round trip length of the resonator cavity was equal to twice the laser cavity length for maximum coherence in the crystal, given a multimode laser. The path lengths of the pump beam and the resonator input beam were also equalized to the crystal. The lens in the resonator served to re-image the beam to the crystal at each round trip with unity magnification. This helped confine the beam to the small clear aperture of the crystal. To test this setup, the input and the pump beams were allowed to write an index grating in the crystal for 1-5 minutes. Then, the input was blocked and the output of the resonator was observed. On out initial attempts, oscillation was not sustained, and the output intensity monotonically decreased as the pump beam diffracted off the index grating and erased it over a time span of about 20-30 seconds. After improved alignment of the resonator, the output took longer to decay. However, only after the lab air-conditioning was turned off were we able to observe sustained oscillation. When this occurred, the output of the resonator increased and decreased in intensity, but would remain indefinitely after blocking the input beam. The airflow from the air-conditioning, or the sound from it, had caused phase shifts which destroyed grating reinforcement in the crystal. Even without the air conditioning on, a single hand-clap near the resonator was enough to quench the oscillation.

With this minimal success, it was decided to employ a higher-powered argon-ion laser operating at 514.5 nm wavelength to continue the experiments. Higher power serves to decrease the response time of the barium titanate. More importantly, etalons are available to allow single longitudinal mode operation, resulting in coherence lengths of about 50 m. Longer coherence length allows more of the passes of the circulating beam in the resonator to interact in-phase with the crystal grating and to reinforce it in-phase (assuming air current and vibration effects are controlled).

## 3.0 IMAGE STORAGE IN LITHIUM NIOBATE

The second major component of the proposed system was a holographic storage medium for image. Photorefractive crystals can store volume holograms and are more convenient and versatile than film emulsion holograms. The crystal used for holographic storage should have a much slower response time than the gain medium crystal in this application, so that the storage images are "permanent" as compared to the gain competition process which selects one of them. Lithium niobate was investigated here, since it is much slower than barium titanate.

The first lithium niobate crystal used was 10 x10 x 25 mm and undoped. The geometry was the same as that of Fig. 1, except that the laser was a 20 W argon-ion laser running on the 514.5 nm line with no etalon. With the crossing angle in air 2R = 40 degrees, and 80 mW per beam, the maximum diffraction efficiency was 3.2%, measured after one hour of writing. This value was lower than anticipated, probably due to ambient vibrations causing washout of the index grating over the exposure time. At this crossing angle the grating period in the crystal is 0.95 μm. To reduce the sensitivity to vibrations, the crossing angle was decreased to 2R = 14 degrees, corresponding to a grating period of about 2.5 μm. The experiment was repeated, with the results summarized in Table 2. The peak diffraction efficiency was 21% at the end of the 15 minute writing period. The 15 minute write resulted in a total exposure of 1 $kJ/cm^2$ per beam, similar to the exposure used in Ref. 2. The experiment was repeated with 100 mW in beam 1 and 11 mW in beam 2, but no measurable diffraction was observed after 20 minutes.

The lithium niobate crystal did not need to be 25 mm thick; crystals measuring 1 mm thick are more commonly used for this application. Additionally, iron doping should be used to enhance two-beam coupling (ref. 4). We investigated an iron doped sample measuring 10 x 10 x 10 mm, but it was unsuitable because of its thickness. Absorption in this crystal led to a large insertion loss and optical damage in the bulk of the crystal at power levels of less than 80 mW per beam.

## 4.0 CONCLUSIONS

Simple arithmetic dictated that the combined system would not work. The best gain achieved was 3 and the best diffraction efficiency was 20%. Multiplying these numbers together gives a round trip net gain of 60% which is less than the 100% needed for sustained oscillation.

Certainly, a number of things could have been done to raise the gain and the diffraction efficiency, perhaps leading to an operational holographic ring resonator. Indeed, other research groups, primarily Dana Anderson's group at the University of Colorado at Boulder, have achieved this. The primary improvements would be 1) a high optical quality barium titanate crystal with good two-beam coupling gain, possibly one with a 45 degree z-cut, 2) a thin lithium niobate crystal with an optimized level of iron doping, and 3) a functioning argon-ion laser with a stabilized etalon for single mode operation. These material improvements, along with careful choice of crossing angles and resonator alignment, would probably be sufficient.

Several disadvantages of this overall approach to an associative memory would remain, however. One is the high sensitivity to ambient vibrations and air movement. This requires careful engineering of the system to avoid degradation of the crystal index gratings. Another is the theoretical complexity of the interactions occurring in the photorefractive crystals. While theoretical progress has been made (ref. 5), the theory is not adequate to predict the behavior of a complete ring resonator associative memory. How similar must an input be to trigger the recall of a stored image? Issues of crosstalk between holographic gratings and the role of competing processes such as self-fanning and phase-conjugation are also very complex.

The ring resonator approach is elegant in the sense that the image classification is done "automatically." However, this same simplicity of design is also a drawback in that the performance of the system is not easily tunable. It either will recall stored images or it will not, and there is little that can be done to control the mapping of input to output. The theoretical complexity of the photorefractive interactions force a trial-and-error approach to determine capabilities of the system. It is interesting to note that no papers have been published revealing a ring resonator capable of working with more than one photorefractively stored image, even though a single image system was demonstrated four years ago in Ref. 2.

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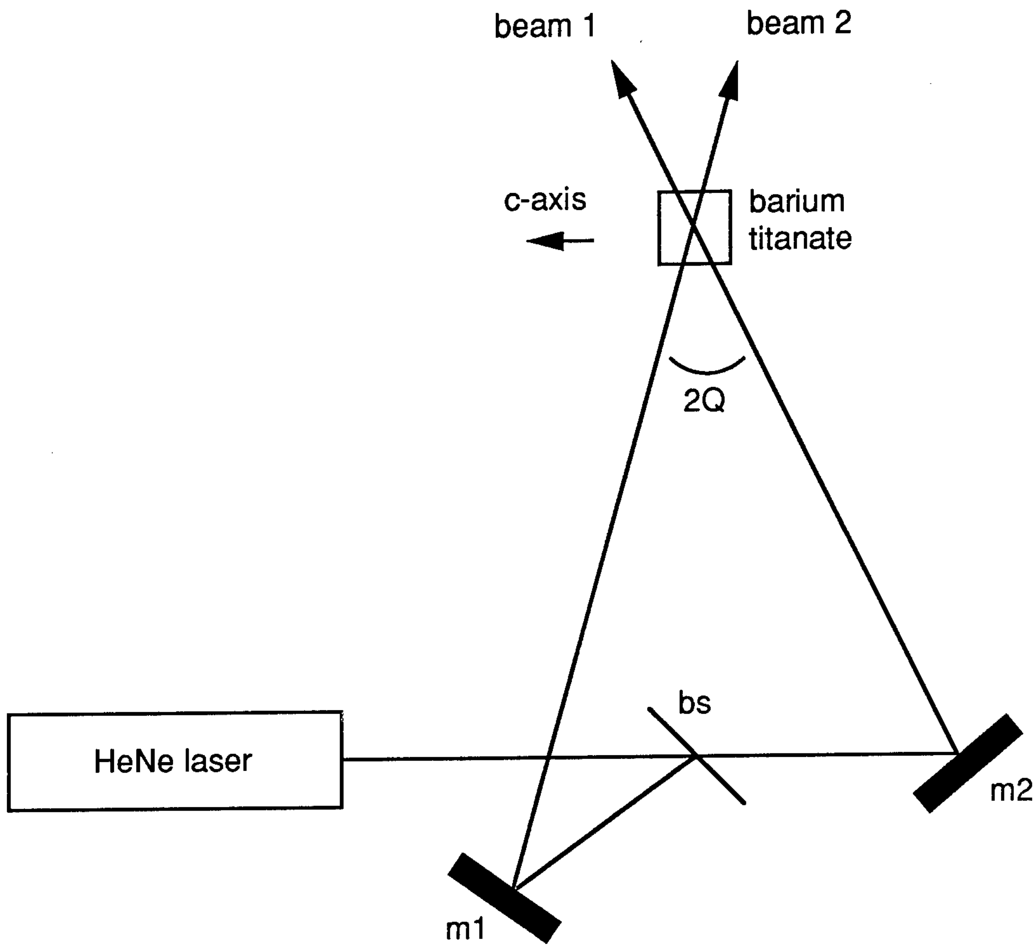


Figure 1. Setup for two-beam coupling measurements. m1 and m2 are mirrors, bs is a beamsplitter.

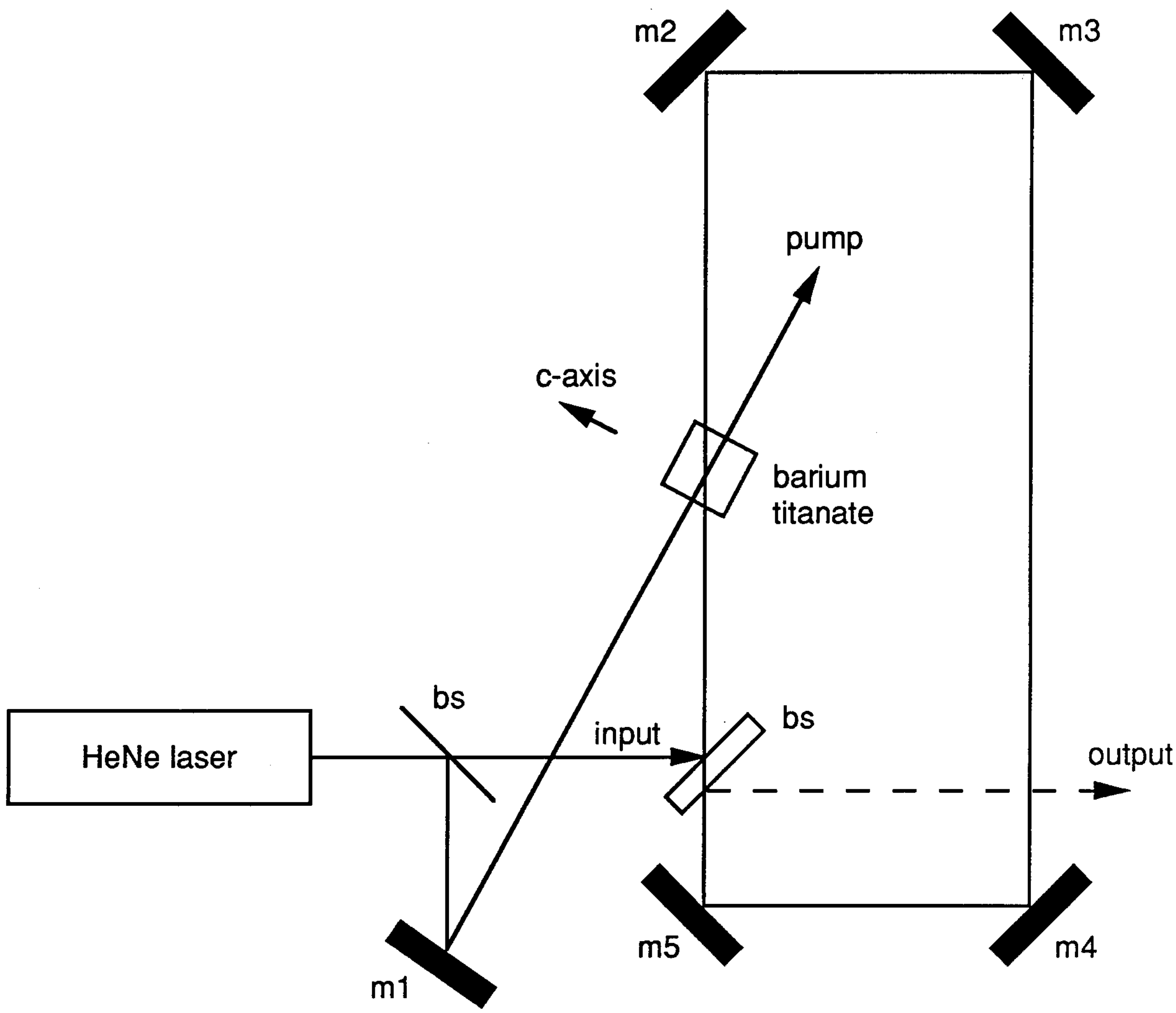


Figure 2. Setup for photorefractive ring resonator. m1-m5 are mirrors, bs's are beamsplitters.

| Case | A | | B | |
|---|---|---|---|---|
| Beam | 1 | 2 | 1 | 2 |
| 1) No crystal | 1.43 | 1.38 | 0.136 | 1.44 |
| 2) With crystal | 0.88 | 0.88 | 0.097 | 0.96 |
| 3) Two-beam coupling | 1.50 | 0.25 | 0.370 | 0.70 |

Table 1. Results for two-beam coupling. All values in milliwatts.

| Beam | 1 | 2 |
|---|---|---|
| 1) No crystal | 73 | 81 |
| 2) With crystal | 53 | 59 |
| 3) Diffracted beam | | |
| write: t = 5 min. | 12 | |
| t = 10 min. | 16 | |
| t = 15 min. | 17 | |
| read: t = 5 min. | 14 | |
| t = 10 min. | 12 | |
| t = 15 min. | 10 | |

Table 2. Results for diffraction efficiency in lithium niobate.
All values in milliwatts.

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